The International Linear Collider
A Global Project

Prepared by: Hiroaki Aihara[1], Jonathan Bagger[2], Philip Bambade[3], Barry Barish[4], Ties Behnke[5], Alain Bellerive[6], Mikael Berggren[5], James Brau[7], Martin Breidenbach[8], Ivanka Bozovic-Jelisavcic[9], Philip Burrows[10], Massimo Caccia[11], Paul Colas[12], Dmitri Denisov[13], Gerald Eigen[14], Lyn Evans[15], Angeles Faus-Golfe[3], Brian Foster[5,10], Keisuke Fujii[16], Juan Fuster[17], Frank Gaede[5], Jie Gao[18], Paul Grannis[19], Christophe Grojean[5], Andrew Hutton[20], Marek Idzik[21], Andrea Jeremie[22], Kiyotomo Kawagoe[23], Sachio Komamiya[1], Tadeusz Lesiak[24], Aharon Levy[25], Benno List[5], Jenny List[5], Shinichiro Michizono[16], Akiya Miyamoto[16], Joachim Mnich[5], Hugh Montgomery[20], Hitoshi Murayama[26], Olivier Napoly[12], Yasuhiro Okada[16], Carlo Pagani[27], Michael Peskin[8], Roman Poeschl[3], Francois Richard[3], Aidan Robson[28], Thomas Schoerner-Sadenius[5], Marcel Stanitzki[5], Steinar Stapnes[15], Jan Strube[29,7], Atsuto Suzuki[30], Junping Tian[1], Maksym Titov[12], Marcel Vos[17], Nicholas Walker[5], Hans Weise[5], Andrew White[31], Graham Wilson[32], Marc Winter[33], Sakue Yamada[1,16], Akira Yamamoto[16], Hitoshi Yamamoto[34] and Satoru Yamashita[1].

[1]*U. Tokyo,* [2]*TRIUMF,* [3]*LAL-Orsay/CNRS,* [4]*Caltech,* [5]*DESY,*
[6]*Carleton U.,* [7]*U. Oregon,* [8]*SLAC,* [9]*INN VINCA, Belgrade,*
[10]*Oxford U.,* [11]*U. Insubria,* [12]*CEA/Irfu, U. Paris-Saclay,*
[13]*Fermilab,* [14]*U. Bergen,* [15]*CERN,* [16]*KEK,* [17]*IFIC,*
U. Valencia-CSIC, [18]*IHEP,* [19]*Stony Brook U.,* [20]*Jefferson Lab,*
[21]*AGH, Kraków,* [22]*LAPP/CNRS,* [23]*Kyushu U.,* [24]*IFJPAN,*
Kraków,[25]*Tel Aviv U.,* [26]*U. California, Berkeley,* [27]*INFN,*
[28]*U. Glasgow,* [29]*PNNL,* [30]*Iwate Prefecture U.,* [31]*U. Texas,*
Arlington, [32]*U. Kansas,* [33]*IPHC/CNRS,* [34]*U. Tohoku*

(***Representing the Linear Collider Collaboration and the global ILC community.***)

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Abstract

A large, world-wide community of physicists is working to realise an exceptional physics program of energy-frontier, electron-positron collisions with the International Linear Collider (ILC). This program will begin with a central focus on high-precision and model-independent measurements of the Higgs boson couplings. This method of searching for new physics beyond the Standard Model is orthogonal to and complements the LHC physics program. The ILC at 250 GeV will also search for direct new physics in exotic Higgs decays and in pair-production of weakly interacting particles. Polarised electron and positron beams add unique opportunities to the physics reach. The ILC can be upgraded to higher energy, enabling precision studies of the top quark and measurement of the top Yukawa coupling and the Higgs self-coupling.

The key accelerator technology, superconducting radio-frequency cavities, has matured. Optimised collider and detector designs, and associated physics analyses, were presented in the ILC Technical Design Report, signed by 2400 scientists.

There is a strong interest in Japan to host this international effort. A detailed review of the many aspects of the project is nearing a conclusion in Japan. Now the Japanese government is preparing for a decision on the next phase of international negotiations, that could lead to a project start within a few years. The potential timeline of the ILC project includes an initial phase of about 4 years to obtain international agreements, complete engineering design and prepare construction, and form the requisite international collaboration, followed by a construction phase of 9 years.

Supporting documents web page:
`https://ilchome.web.cern.ch/content/ilc-european-strategy-document`

Contact persons: James Brau (jimbrau@uoregon.edu), Juan Fuster(Juan.Fuster@ific.uv.es), Steinar Stapnes (Steinar.Stapnes@cern.ch)

I. INTRODUCTION

A central issue in particle physics today is the search for new phenomena needed to address shortcomings of the highly successful Standard Model (SM). These new effects can manifest themselves as new particles, new forces, or deviations in the predictions of the SM derived from high-precision measurements. While the SM is theoretically self-consistent, it leaves many issues of particle physics unaddressed. It has no place for the dark matter and dark energy observed in the cosmos, and it cannot explain the excess of matter over antimatter. It has nothing to say about the mass scale of quarks, leptons, and Higgs and gauge bosons, which is much less than the Planck scale. It has nothing to say about the large mass ratios among these particles. These and other issues motivate intense efforts to challenge the predictions of the SM and search for clues to what lies beyond it.

The Higgs boson, discovered in 2012 at the Large Hadron Collider (LHC), is central to the SM, since it is the origin of electroweak symmetry-breaking and gives mass to all known elementary particles. The study of the properties and interactions of the Higgs boson is thus of utmost importance.

The International Linear Collider (ILC) has the capabilities needed to address these central physics issues. It will extend and complement the LHC physics program. First and most importantly, it provides unprecedented precision in the measurements and searches needed to detect deviations from the SM. Already in its first stage, the ILC will have a new level of sensitivity to test the well-defined SM expectations for the Higgs boson properties, and to advance many other tests of SM expectations. The well-defined collision energy at the ILC, together with highly polarised beams, low background levels and absence of spectator particles, will enable these precision measurements. A linear collider allows straightforward energy upgrades, which bring new processes into play. The energy upgrades will allow the ILC to remain a powerful discovery vehicle for decades. Finally, and critically, the technology is mature, ready for implementation today.

For more than twenty years the worldwide community has been engaged in a research program to develop the technology required to realise a high-energy linear collider. As the linear collider technology has progressed, committees of the International Committee for Future Accelerators (ICFA) have guided its successive stages. In the mid-1990's, as various technology options to realise a high-energy linear collider were emerging, the Linear Collider Technical Review Committee developed a standardised way to compare these technologies in terms of parameters such as power consumption and luminosity. In 2002, ICFA set up a second review panel which concluded that both warm and cold technologies had developed to the point where either could be the basis for a linear collider. In 2004, the International Technology Review Panel (ITRP) was charged by ICFA to recommend an option and focus the worldwide R&D effort. This panel chose the superconducting radiofrequency technology (SCRF), in a large part due to its energy efficiency and potential for broader applications. The effort to design and establish the technology for the linear collider culminated in the publication of the Technical Design Report (TDR) for the International Linear Collider (ILC) in 2013 [1].

The collider design is thus the result of nearly twenty years of R&D. The heart of the ILC, the superconducting cavities, is based on pioneering work of the TESLA Technology Collaboration. Other aspects of the technology emerged from the R&D carried out for the JLC/GLC and NLC projects, which were based on room-temperature accelerating structures. From 2005 to the publication of the TDR [1] in 2013, the design of the ILC accelerator was conducted under the mandate of ICFA as a worldwide international collaboration, the Global Design Effort (GDE). Since 2013, ICFA has placed the international activities for both the ILC and CLIC projects under a single organisation, the Linear Collider Collaboration (LCC). Today the European XFEL provides an operating 1/10-scale demonstration of the fundamental SCRF technology.

Once the mass of the Higgs boson was known, it was established that the linear collider could start its ambitious physics program with an initial centre-of-mass energy of 250 GeV, with a reduced cost relative to that in the TDR. In this ILC250 [2], the final focus and beam dumps would be designed to operate at energies up to 1 TeV. Advances in the theoretical understanding of the impact of precision measurements at the ILC250 have justified that this operating point already gives substantial sensitivity to physics beyond the Standard Model [3, 4]. The cost estimate for ILC250 was also carefully evaluated; it is described in Appendix A. It is similar in scale to the LHC project.

In its current form, the ILC250 is a 250 GeV centre-of-mass energy (extendable up to 1 TeV) linear e^+e^- collider, based on 1.3 GHz SCRF cavities. It is designed to achieve a luminosity of $1.35 \cdot 10^{34}$ cm^{-2}s^{-1}, and provide an integrated luminosity of 400 fb^{-1} in the first four years of running and 2 ab^{-1} in a little over a decade. The electron beam will be polarised to 80 %, and the baseline plan includes an undulator-based positron source which will deliver 30 % positron polarisation. Positron production by a 3 GeV S-band injector is an alternative being considered.

The experimental community has developed designs for two complementary detectors, ILD and SiD, as described in [5]. These detectors are designed to optimally address the ILC physics goals, operating in a push-pull configuration. The detector R&D program leading to these designs has contributed a number of advances in detector capabilities with applications well beyond the linear collider program.

This report summarises the current status of this effort, describing the physics reach, the technological maturity of the accelerator, detector, and software/computing designs, plus a short discussion on the further steps needed to realise the project.

II. PHYSICS

The ILC has the ability to begin with a high-precision study of the Higgs boson couplings. At 250 GeV, the ILC also presents many opportunities to discover new particles that go beyond the capabilities of the LHC. Finally, the ILC at 250 GeV opens the door to further exploration of e^+e^- reactions at higher energies. This capability has been clearly demonstrated with detailed simulations of important physics channels including full detector effects. The ILC physics case is reviewed at greater length in the reference document [6].

The Higgs boson is a necessary element of the SM, yet it is to very large extent unknown. In the SM, the Higgs field couples to every elementary particle and provides the mass for all quarks, charged leptons, and heavy vector bosons. The LHC has discovered the Higgs particle and confirmed the presence of the couplings responsible for the masses of the W, Z, t, b, and τ [7]. However, mysteries are still buried here. The Higgs couplings are not universal, as the gauge couplings are, and their pattern (which is also the pattern of lepton and quark masses) is not explained by the SM. The basic phenomenon that provides mass for elementary particles—the spontaneous breaking of the gauge symmetry $SU(2) \times U(1)$—is not explained, and actually cannot be explained, by the SM. The Higgs boson could also couple to new particles and fields that have no SM gauge interactions and are otherwise completely inaccessible to observation. Thus, detailed examination of the Higgs boson properties should be a next major goal for particle physics experiments.

Within the SM, the couplings of the Higgs boson are specified now that the parameters of the model, including the Higgs boson mass, are known. Expected knowledge improvements of SM parameters in the 2020's will allow these couplings to be predicted to the part-per-mille level [8]. Models of new physics modify these predictions at the 10% level or less, detectable by precision experiments. Most importantly, different classes of models affect the various Higgs couplings differently, so that systematic measurement of the Higgs couplings can reveal clues to the nature of the new interactions. The precision study of the Higgs boson interactions then provides a new method both to *discover* the presence of physics beyond the SM and to *learn* about its nature.

The couplings of the Higgs boson are now being studied at the LHC. The LHC experiments have made remarkable progress in measuring the ratios of couplings of the Higgs boson, and they expect impressive further progress, as documented in the HL-LHC Yellow Report [9]. The uncertainty projections from the Yellow Report are shown in Fig. 1. These measurements are very challenging. Aside from events in which the Higgs boson appears as a narrow resonance (the decays to $\gamma\gamma$ and 4ℓ), Higgs boson events are not visibly distinct from SM background events. Analyses start from signal/background ratios of about 1/10 even in the most sensitive kinematic regions (better for VBF production, but worse for VH production with $H \to b\bar{b}$) and then apply strong selections to make the Higgs signal visible. To reach the performance levels predicted in the Yellow Report, it is necessary to determine the level of suppression of SM backgrounds to better than 1% accuracy. At the same time, these projected uncertainties do not allow the LHC experiments to observe, for example, an anomaly of 5% in the hWW coupling to 3σ significance. To prove the presence of such small deviations, which are typical in new physics models, a different approach is required.

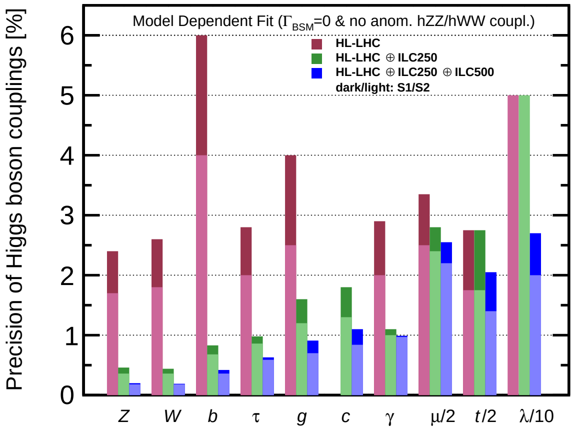

FIG. 1. Projected Higgs boson coupling uncertainties for the LHC and ILC using the model-dependent assumptions appropriate to the LHC Higgs coupling fit. The dark- and light-red bars represent the projections in the scenarios S1 and S2 presented in [9, 10]. The scenario S1 refers to analyses with our current understanding; the scenario S2 refers to more optimistic assumptions in which experimental errors decrease with experience. The dark- and light-green bars represent the projections in the ILC scenarios in similar S1 and S2 scenarios defined in [6]. The dark- and light-blue bars show the projections for scenarios S1 and S2 when data from the 500 GeV run of the ILC is included. The same integrated luminosities are assumed as for Figure 2. The projected uncertainties in the Higgs couplings to $\mu\mu$, tt, and the self-coupling are divided by the indicated factors to fit on the scale of this plot.

What is needed for a precision Higgs boson measurement program is a new experimental method in which all individual Higgs boson decays are manifest and can be studied in detail. This is provided by the reaction $e^+e^- \to ZH$ at 250 GeV in the centre-of-mass. At this CM energy, the lab energy spectrum of Z bosons shows a clear peak at 110 GeV, corresponding to recoil against the Higgs boson, on top of a small and precisely calculable SM background. Events in this peak tag the Higgs boson independently of the mode of Higgs boson decay. These events then give a complete picture of Higgs boson decays, including all SM leptonic and hadronic final states and also invisible or partially visible exotic modes.

Further, since the cross section for Higgs production can be measured independently of any property of the

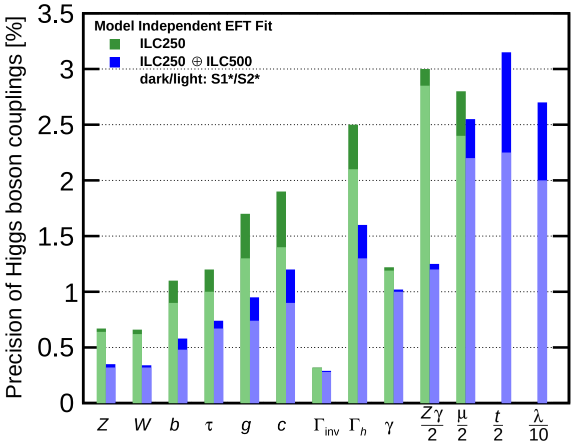

FIG. 2. Projected Higgs boson coupling uncertainties for the ILC program at 250 GeV and an energy upgrade to 500 GeV, using the highly model-independent analysis presented in [3]. This analysis makes use of data on $e^+e^- \to W^+W^-$ in addition to Higgs boson observables and also incorporates projected LHC results, as described in the text. Results are obtained assuming integrated luminosities of $2\,\mathrm{ab}^{-1}$ at 250 GeV and $4\,\mathrm{ab}^{-1}$ at 500 GeV. All estimates of uncertainties are derived from full detector simulation. Note that the projected uncertainties in the Higgs couplings to $Z\gamma$, $\mu\mu$, tt, and the self-coupling are divided by the indicated factors to fit on the scale of this plot. The scenario S1* refers to analyses with our current understanding; the scenario S2* refers to more optimistic assumptions in which experimental errors decrease with experience. A full explanation of the analysis and assumptions underlying these estimates is given in [6].

Higgs boson, the total Higgs width and hence the scale of Higgs couplings can be determined and the individual couplings can be absolutely normalised. Each individual coupling can be compared to its SM prediction.

In the description of new physics by an $SU(2) \times U(1)$-invariant effective field theory (EFT), there exist both a remarkable complementarity and a synergy between measurements in Higgs physics, in precision electroweak observables and in diboson production. This calls for a global approach in interpreting data from the three different sectors. The high precision in the measurement of $e^+e^- \to W^+W^-$ at an e^+e^- collider then works to improve the Higgs-coupling determination. Beam polarisation at the ILC is also a powerful tool to separate the contributions of different EFT coefficients. In addition, a number of readily interpreted Higgs boson observables that will be measured at the HL-LHC can be used, especially the ratio of branching ratios $BR(H \to \gamma\gamma)/BR(H \to ZZ^*)$. In [3], it is shown that, by the use of this information, it is possible to fit *all* relevant EFT coefficients *simultaneously*, giving a determination of Higgs boson couplings that is as model-independent as the underlying EFT description itself.

The uncertainties in cross section and $\sigma \cdot BR$ measurements that contribute to the EFT determination of the Higgs boson couplings were estimated using full-simulation analyses. These analyses incorporate the detailed detector designs described in Section IV A and the performance levels justified by R&D as reviewed in Section IV B. This gives our estimates denoted S1* (See Figure 2 caption). The inputs are described in more detail in [6]. For the nominal ILC program at 250 GeV, the Higgs coupling to b quarks is expected to be measured to 1.1% accuracy and the couplings to W and Z to 0.7% accuracy. The full set of expected uncertainties is shown in Fig. 2.

In a manner similar to the estimates in [9], a more optimistic scenario S2* is defined, assuming that detector performance can be improved with experience. The precise scheme is described in [6]. The S2* estimates are also shown in Fig. 2. The blue bars in the figure show the improvement in the errors when running at 500 GeV is also included. The discovery of any anomaly at 250 GeV can be confirmed using additional reactions such as WW-fusion production of the Higgs boson. Measurements at this level can discover—and distinguish—models of new physics over a wide space of possibilities, even for models in which the predicted new particles are too heavy to be discovered at the LHC [3].

Figure 1 compares the ILC projections to those given in the HL-LHC Yellow Report [9] in their scenarios S1 and S2. The LHC projections include model-dependent assumptions. To assist the comparison, these assumptions are imposed also in the ILC analyses. The uncertainties in the extracted Higgs couplings under these assumptions [6] are shown as the S1 and S2 values in the figure. The blue bars again show the effect of adding a data set at 500 GeV, as described in [6].

In addition to its decays predicted in the SM, the Higgs boson could have additional decays to particles with no SM gauge interactions. These decays may include invisible decays (*e.g.*, to a pair of dark matter particles χ) or partially invisible decays (*e.g.*, to $b\bar{b}\chi\chi$). The ILC can robustly search for all types of exotic decays to the part-per-mille level of branching fractions [11].

The ILC can also search for particles produced through electroweak interactions, closing gaps that are left by searches at the LHC. These include searches for dark matter candidates and for the radion and dilaton of extra-dimensional models. An important example is the Higgsino of supersymmetric models. If the mass differences among Higgsinos are smaller than a few GeV—as predicted in currently allowed models—then Higgsinos of 100 GeV mass would be produced copiously at the LHC, but this production would not be registered by LHC triggers. In the clean environment of the ILC, even such difficult signatures as this would be discovered and the new particles studied with percent-level precision [12].

ILC precision measurements of $e^+e^- \to f\bar{f}$ processes at 250 GeV have a sensitivity to new electroweak gauge bosons comparable to (and complementary with) direct searches at the LHC. Though the center of mass energy is only a little higher than that of LEP 2, the ILC will collect an event sample 1000 times greater, with detec-

Quantity	Symbol	Unit	Initial	Upgrades	
Centre-of-mass energy	$\sqrt{s}$	GeV	250	500	1000
Luminosity	$\mathcal{L}$	$(10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1})$	1.35	1.8	4.9
Repetition frequency	f_{rep}	Hz	5	5	4
Bunches per pulse	n_{bunch}	1	1312	1312	2450
Bunch population	N_{e}	10^{10}	2	2	1.74
Linac bunch interval	Δt_{b}	ns	554	554	366
Beam current in pulse	I_{pulse}	mA	5.8	5.8	7.6
Beam pulse duration	t_{pulse}	μs	727	727	897
Average beam power	P_{ave}	MW	5.3	10.5	27.2
Norm. hor. emitt. at IP	$\gamma\epsilon_{\mathrm{x}}$	μm	5	10	10
Norm. vert. emitt. at IP	$\gamma\epsilon_{\mathrm{y}}$	nm	35	35	35
RMS hor. beam size at IP	σ^*_{x}	nm	516	474	335
RMS vert. beam size at IP	σ^*_{y}	nm	7.7	5.9	2.7
Site AC power	P_{site}	MW	129	163	300
Site length	L_{site}	km	20.5	31	40

TABLE I. Summary table of the ILC accelerator parameters in the initial 250 GeV staged configuration and possible upgrades.

tors dramatically superior in their heavy flavor identification and other capabilities. Polarisation plays a key role since it allows the electroweak couplings to be disentangled, with particular sensitivity to right-handed couplings. The reaction $e^+e^- \to b\bar{b}$ is of special interest since it can receive corrections not only from new electroweak interactions but also from new physics that acts primarily on the Higgs and the heavy quark doublet (t, b) [13, 14].

The ILC at 250 GeV can be the first step to the study of e^+e^- reactions at higher energy. A linear e^+e^- collider is extendable in energy by making the accelerator longer or by increasing the acceleration gradient. Extensions to 500 GeV and 1 TeV were envisioned in the ILC Technical Design Report [1]. The aims of this higher-energy program are discussed in detail in [6]. They include the measurement of the top-quark mass with a precision of 40 MeV, measurements of the top-quark electroweak couplings to the per-mille level, measurement of the Higgs coupling to the top quark to 2% accuracy, and measurement of the triple-Higgs boson coupling to 10% accuracy. Higher energy stages of the ILC will also extend searches for new particles with electroweak interactions and will give sensitivity to new Z' bosons of mass 7–12 TeV. Eventually, the ILC tunnel could be the host for very high gradient electron accelerators reaching energies much higher than 1 TeV. The ILC promises a long and bright future beyond its initial 250 GeV stage.

III. COLLIDER

The fundamental goal of the design of the ILC is to fulfill the physics objectives outlined in this document with high energy-efficiency. In the design, the overall power consumption of the accelerator complex during operation is limited to 129 MW at 250 GeV and 300 MW at 1 TeV, which is comparable to the power consumption of CERN today. This is achieved by the use of SCRF technology for the main accelerator, which offers a high RF-to-beam efficiency through the use of superconducting cavities. The cavities are operated at 1.3 GHz, where high-efficiency klystrons are commercially available. At accelerating gradients of 31.5 to 35 MV/m, this technology offers high overall efficiency and reasonable investment costs, even considering the cryogenic infrastructure needed for the operation at 2 K. Some relevant parameters are given in Table I.

The underlying TESLA SCRF technology is mature, with a broad industrial base throughout the world, and is in use at a number of free-electron-laser facilities that are in operation (European XFEL at DESY), under construction (LCLS-II at SLAC), or in preparation (SHINE in Shanghai) in the three regions that have contributed to the ILC technology. In preparation for the ILC, Japan and the U.S. have founded a collaboration for further cost optimisation of the TESLA technology. In recent years, new surface treatments during the cavity preparation process, such as the so-called nitrogen infusion, have been developed at Fermilab and elsewhere. These offer the prospect of achieving higher gradients and lower loss rates than assumed in the TDR, using a less expensive surface-preparation scheme. This would lead to a further cost reduction over the current estimate.

The design goal of energy efficiency fits well into the "Green ILC" concept [15] that pursues a comprehensive approach to a sustainable laboratory. Current European Research and Innovation programmes include efficiency studies for the ILC and other accelerators. A model is the recently inaugurated European Spallation Source ESS in Sweden, which followed the 4R strategy: Responsible, Renewable, Recyclable and Reliable.

When the Higgs boson was discovered in 2012 and the Japan Association of High Energy Physicists (JAHEP) made a proposal to host the ILC in Japan, the Japanese ILC Strategy Council conducted a survey of possible sites for the ILC in Japan, looking for suitable geological conditions for a tunnel up to 50 km in length, and the possibility to establish a laboratory where several thousand international scientists could work and live. The candidate site in the Kitakami region in northern Japan, close to the larger cities of Sendai and Morioka, was found to be the best option. The site offers a large, uniform granite formation, with no active seismic faults, that is well suited for tunnelling. Even in the great Tohoku earthquake of 2011, underground installations in this rock formation were essentially unaffected. This underlines the suitability of this candidate site.

Figure 3 shows a schematic overview of the initial-stage accelerator with its main subsystems. The accelerator extends over 20.5 km, with two main arms that are dominated by the electron and positron main linacs, at a 14 mrad crossing angle.

Electrons are produced by a polarised electron gun located in the tunnel of the positron beam-delivery system. A Ti:sapphire laser impinges on a photocathode with a strained GaAs/GaAsP superlattice structure, which will provide 90 % electron polarisation at the source, resulting in more than 80 % polarisation at the interaction point. The design is based on the electron source of the SLAC

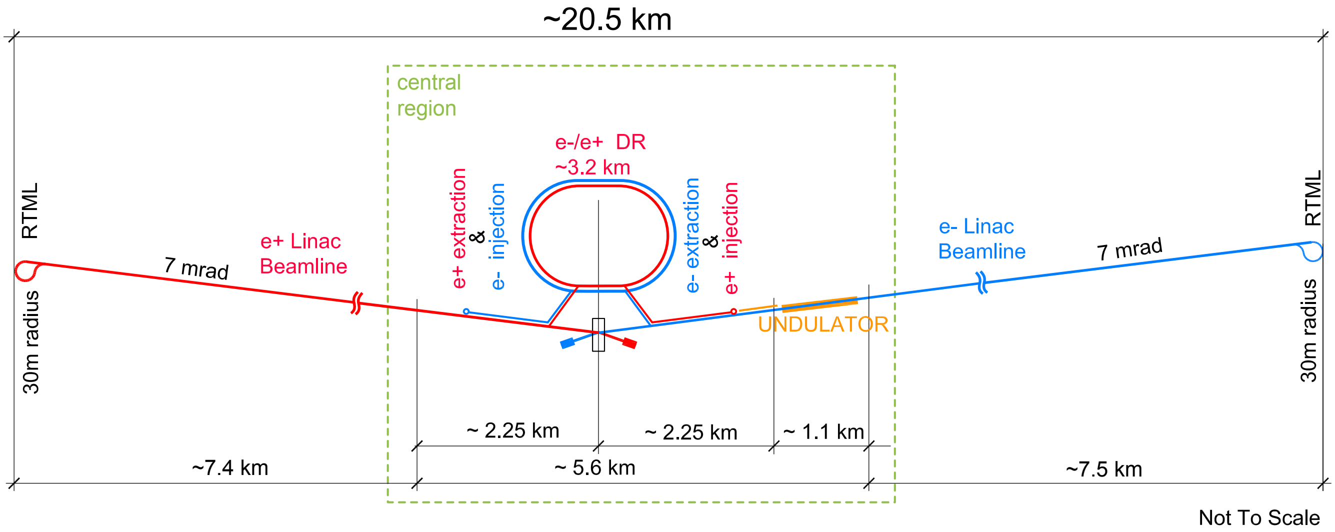

FIG. 3. Schematic layout of the ILC in the 250 GeV staged configuration.

Linear Collider (SLC).

Two concepts for positron production are considered. The baseline solution employs superconducting helical undulators at the end of the electron main linac, producing polarised photons that are converted to positrons in a rotating target, with a 30 % longitudinal polarisation. This positron-production scheme requires an operational electron linac delivering a beam close to its nominal energy of 125 GeV, which is a complication for commissioning and operation. An alternative design, the electron-driven source, utilises a dedicated S-band electron accelerator to provide a 3 GeV beam that is used to produce positrons by pair production. This source might not provide positron polarisation, but would have advantages for operation at lower electron beam energies and during commissioning. Both concepts are likely to prove viable when the requisite engineering effort can be devoted to their design. The current accelerator design is compatible with either option. A decision between the alternatives will be made before commencement of the detailed engineering design, based on their relative physics potential, costs, and technical maturity.

Electrons and positrons are injected at 5 GeV into the centrally placed 3.2 km-long damping-ring complex, where their normalised emittance is reduced to 20 nm (4 μm) in the vertical (horizontal) plane within 100 msec. These emittance numbers are well in line with the performance of today's storage rings for advanced light sources. To achieve the necessary damping time constant, the damping ring is equipped with 54 superconducting wigglers.

The damped beams are transported to the beginning of the main accelerator by two low-emittance beam-transport lines. A two-stage bunch compressor from 5 and 15 GeV reduces the longitudinal bunch length to 300 μm before the beams are accelerated to 125 GeV in the two main linacs.

The main linacs accelerate the beams in superconducting cavities made of niobium, operating at 1.3 GHz frequency and a temperature of 2.0 K. Each cavity has 9 cells and is 1.25 m long. The mean accelerating gradient will be 31.5 to 35 MV/m. Cavities are mounted in 12 m-long cryomodules that house 9 cavities or 8 cavities plus a quadrupole unit for beam focusing. The cryomodules provide cooling and thermal shielding and contain all necessary pipes for fluid and gaseous helium at various temperatures. No separate helium transport line is necessary.

Cryomodules of this type have been in continuous operation since 2000 in the TESLA Test Facility (TTF, now FLASH), since 2016 at the FAST facility at Fermilab where the ILC specification of the 31.5 MeV/m beam acceleration gradient was demonstrated [16], and, since 2017, 97 of these cryomodules have been in operation at the European XFEL. This proves their long-term stability. Cost and performance estimates for the ILC cryomodules are based on the experience from these facilities, and thus can be regarded with high confidence.

The RF power for the cavities is generated by commercially available 10 MW klystrons with an efficiency of 65 %. The pulse modulators will use a new, modular and cost-effective semiconductor design developed at SLAC, the MARX modulator.

The cryogenic design for the superconducting cavities is planned with six cryo plants for the main linacs, each with a size similar to those operating at CERN (8 plants for the LHC), DESY (for HERA/ XFEL) and Fermilab (for the Tevatron). Two smaller plants would supply the central region, including the preaccelerators of the sources and the damping rings.

Finally, the beam-delivery system focuses the beams to the required size of 516 nm × 7.7 nm. A feedback system, which profits from the relatively long inter-bunch separation of 554 ns, ensures the necessary beam stability. The necessary nano-beam technology and feedback control has been tested at the Accelerator Test Facility 2 (ATF-2) at KEK, where beam sizes of 41 nm have been demonstrated [17]; these correspond to the ILC design goal within 10 % after scaling for different beam energies.

The TDR baseline design assumed a centre-of-mass energy of $\sqrt{s} = 500\,\mathrm{GeV}$, upgradeable to a final energy of 1 TeV. After the discovery of the Higgs boson in 2012, interest grew for an accelerator operating as a "Higgs factory" at $\sqrt{s} = 250\,\mathrm{GeV}$, slightly above the maximum for Zh production. The design for a 250 GeV version of the ILC has recently been presented in a staging report by the LCC directorate [2] and was endorsed by ICFA.

This staged version of the ILC would have two main linac tunnels about half the length of the 500 GeV TDR design (6 km instead of 11 km). Other systems, in particular the beam-delivery system and the main dumps, would retain the dimensions of the TDR design. Then the ILC250 could be upgraded to energies of 500 GeV or even 1 TeV with a reasonable effort, without extensive modifications to the central region. Recent studies of rock vibrations from tunnel excavation in a similar geology indicate that the necessary additional main linac tunnels could be largely constructed during ILC operation, so that an energy upgrade could be realised with an interruption in data taking of only about 2 years, compatible with a smooth continuation of the physics programme.

Another upgrade option, which could come before or after an energy upgrade, is a luminosity upgrade. Doubling the luminosity by doubling the number of bunches per pulse to 2625 at a reduced bunch separation of 366 ns would require 50 % more klystrons and modulators and an increased cryogenic capacity. The damping rings would also permit an increase of the pulse repetition rate from 5 to 10 Hz at 250 GeV . This would require a significant increase in cryogenic capacity, or running at a reduced gradient after an energy upgrade. The projections for the physics potential of the ILC250 are based on a total integrated luminosity of $2\,\mathrm{ab}^{-1}$, which assumes at least one luminosity upgrade.

IV. DETECTORS

The detector concepts proposed for the ILC have been developed over the past 15 years in a strong international effort. They reflect the requirements placed on the detectors from the science, and have folded in the constraints from the design of the machine, in particular the special properties of the interaction region. They incorporate the results of the R&D effort described below.

A. The full detector systems, ILD and SiD

The main guiding principles for the full detector systems are:

- The detector must have excellent track momentum resolution, of about $\delta(1/p) = 2 \times 10^{-5}\mathrm{GeV}^{-1}$. The benchmark here is the analysis of the di-lepton mass in the process $e^+e^- \to HZ \to H\ell^+\ell^-$. This reaction allows the reconstruction of the Higgs mass, independently of its decay mode, via the reconstruction of the lepton recoil momentum. The Higgs boson mass is important by itself, but it is also a crucial input in the precise SM prediction of the Higgs boson properties. Stringent momentum resolution requirements must be reached to meet the mass resolution goal.

- Many physics measurements depend on the flavor identification of heavy quarks and leptons. For this, very powerful vertex detectors are needed. Both for the known Higgs boson and, typically, for extended Higgs particles, the most prominent decays are to third-generation species. Many other physics processes also lead to complex final states containing bottom or charm quarks. A superb vertex detector is needed to reconstruct these long-lived particles precisely and with high efficiency. For example, the position of the reconstructed secondary vertex should be found with a precision of better than $4\,\mu\mathrm{m}$.

- The momenta of the full set of final-state particles are best reconstructed with the Particle Flow Algorithm (PFA). This technique combines the information from the tracking systems and from the calorimetric systems to reconstruct the energy and the direction of all charged and neutral particles in the event. To minimise overlaps between neighboring particles, and to maximize the probability to correctly combine tracking and calorimeter information, excellent calorimeters with very high granularity are needed. The agreed-upon goal is a jet energy resolution of 3% – an improvement of about a factor of two over the LHC detectors.

- Many physics signatures predict some undetectable particles which escape from the detector. These can only be reconstructed by measuring the missing energy and 3-momentum in the event. This requires that the detector is as hermetic as possible. Particular care must be given to the region at small angles surrounding the beampipe.

Compared to the last large-scale detector project in particle physics, the construction and upgrade of the LHC detectors, the emphasis for linear collider detectors is shifted towards ultimate precision. This requires detector technologies with new levels of performance. It also requires the minimisation of passive material in the detector at an unprecedented level, with strict management and control of services and, in particular, thermal management of the detector. As a benchmark, the total material in front of the electromagnetic calorimeter should not exceed a few percent of a radiation length. This is possible due to the relatively low levels of radiation, compared to the LHC, for example. Significant

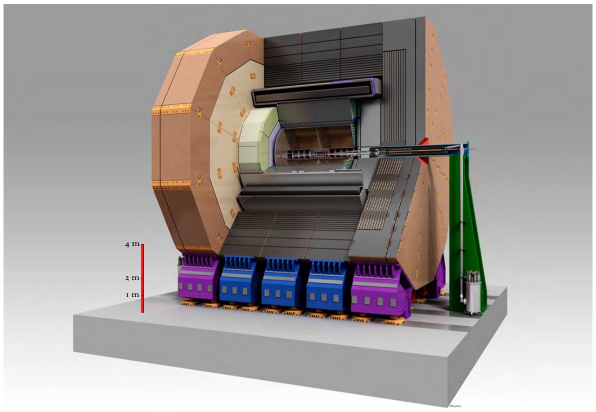

FIG. 4. The ILD detector concept.

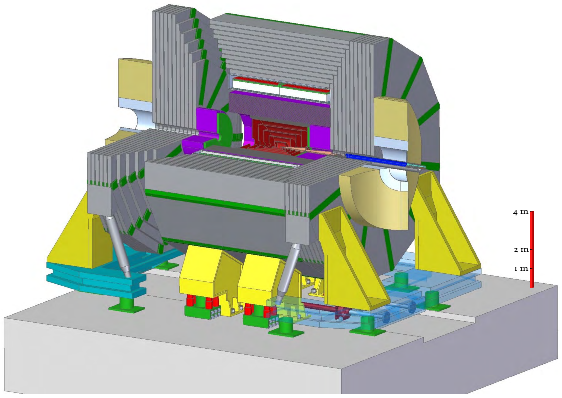

FIG. 5. The SiD detector concept.

technological R&D was needed to demonstrate the feasibility of this goal.

Over the last decade, two detector concepts have emerged from the discussions and studies in the community. Both are based on the assumption that the particle-flow technique will play a central role in the event reconstruction. Both therefore have highly granular calorimeters placed inside the solenoid coil and excellent trackers and vertexing systems. The two approaches differ in the choice of tracker technology, and in the approaches taken to maximise the overall precision of the event reconstruction. ILD (Fig. 4) has chosen a gaseous central tracker, a time projection chamber, combined with silicon detectors inside and outside the TPC. SiD (Fig. 5) relies on an all-silicon solution, similar to the LHC detectors, although with much thinner silicon layers. ILD would optimise the particle-flow resolution by making the detector large, thus separating charged and neutral particles. SiD keeps the detector more compact, and compensates by using a higher central magnetic field. Both approaches have demonstrated excellent performance through prototyping and simulation, meeting or even exceeding the requirements.

The ILC infrastructure has been designed to allow for two detectors, operated in a so-called push-pull mode. The detectors are mounted on movable platforms, which can be moved relatively quickly in and out of the beam. The goal is to exchange the detectors in the IP and be ready to take data within a day or two.

This baseline design with two detectors has distinct scientific advantages over a one detector arrangement. The push-pull design is much less expensive than that with two separate interaction points. The scientific advantages arise from the complementarity of the detectors, the competition between detector teams, the opportunity for independent cross-checks of new results, and the likely larger community of participants in the scientific program.

For both detector concepts, communities have self-organised and pre-collaborations have formed. Over the last ten years, these organisations have pushed both concepts to a remarkable level of maturity. In close interaction with the different groups performing detector R&D from around the world, they have demonstrated the feasibility of building and operating such high-precision detectors.

European groups have played a central role in these efforts. The ILD concept group is formed from some 70 groups from around the world, with more than half coming from Europe. The SiD collaboration has a strong basis in the Americas, but also relies on significant participation from European groups. Major contributions to the development of all sub-systems have come from Europe. Significant technological breakthroughs, for example in the area of highly granular calorimeters, are strongly driven by European groups.

An important aspect of the detector concept work has been the integration of the detector into the collider and into the proposed site. The location of the experiment in an earthquake-prone area poses challenges which have been addressed through R&D on detector stability, support and service. The scheme to operate two detectors in one interaction region required significant engineering work to demonstrate its feasibility. With strong support from particle physics laboratories in Europe, in particular DESY and CERN, many of the most relevant questions were answered and the feasibility of the approach demonstrated, at least in principle.

B. Detector R&D

The physics demands for high precision challenge the ILC detector designs. Optimal trade-offs between granularity, material, speed and power, and resolution were needed to achieve the performance parameters discussed in Section IV, an order of magnitude improvement in state-of-the-art. Intensive R&D was needed to realise this performance, reliably and at minimal cost, on the subsystem level, and within the complete, integrated detector system [18].

The use of the Particle Flow Algorithm (PFA) for reconstruction of final-state particles based on both tracking and calorimetric information required an integrated approach. Once optimized, the results could be applied to the realistic Monte Carlo simulations of physics performance discussed in Section II. Several variants of calorimeter and tracking subsystems were developed for studies in test beams, sometimes within a 2 T magnetic field. These enabled studies that optimized performance with respect to cost constraints.

Tracking and vertex detector development was driven by pixellated, low-material components with excellent momentum resolution and displaced vertex characterisation, including vertex charge, performances typically exceeding existing experiments by an order of magnitude.

Two main tracker alternatives were investigated: a TPC and silicon sensors, possibly pixelated. TPC R&D addressed mainly the single-point resolution and ion-feedback mitigation with different micro-pattern read-out systems (MicroMegas, GEM, ...), showing performance goals are reached, with an end-cap material budget of less than 30% X_0. Silicon sensor R&D aimed at reducing the material budget; targeted momentum resolution is achieved with a limited number of layers. ATLAS and CMS tracker upgrade R&D contributed, although ILC silicon tracking layers are much thinner with somewhat different solutions. A large-area pixelated tracker may improve performance over silicon-strips in dense jet environments.

Vertex detector R&D explored several thin, highly-granular pixel technologies (CMOS, DEPFET, FPCCD, SoI, ...) that offer the projected spatial resolution and material budget. Intensive efforts focussed on read-out systems that handle the beam-related background hit density. The performance depends on material technology and read-out architecture. Double-sided layers were also investigated establishing feasibility near an e^+e^- interaction point.

PFA requirements lead to very compact, highly-granular calorimetric technologies, including low-power read-out micro-circuits with power pulsing. The CALICE Collaboration studied the major issues for both electromagnetic (ECAL) and hadron calorimeters (HCAL). ECAL R&D concentrated on optimised and cost-effective sensor systems, designs of low-power, pulsed, integrated readout electronics and effective thermal management and calibration strategy, and a mechanical concept combining high stability with minimal passive material zones. A SiW-based full-size prototype was constructed and tested extensively on particle beams. A cost-effective scintillator/photo-sensor solution was also tested.

HCAL prototyping emphasized efficient and precise neutral hadron shower reconstruction. Two options developed with stainless steel conversion material included scintillator tiles with silicon photo-sensors read out with analog electronics, and more highly-segmented RPCs with one or two bit signal encoding.

Test-beam campaigns combining various ECAL and HCAL options demonstrate the relative merits, including PFA processing. The energy and topology resolution requirements have been demonstrated, including in power-pulsing operation.

Very forward calorimeter technologies with robust electron and photon detection for luminosity and operations measurements show satisfactory performance with 1 MGy tolerance. Tungsten absorbers coupled with alternating GaAs sensor planes included fast feedback for beam tuning.

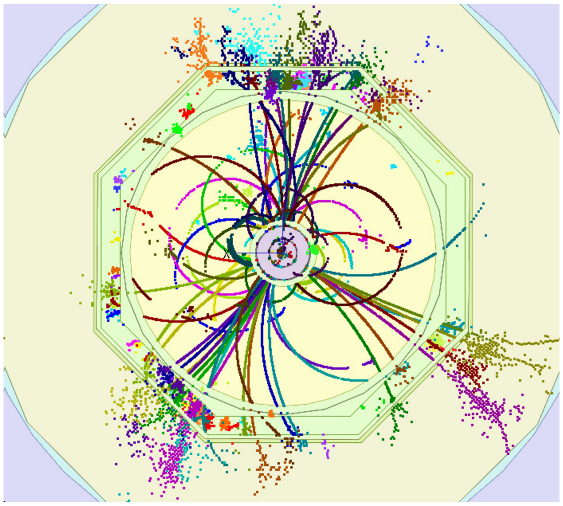

FIG. 6. Fully simulated and reconstructed $t\bar{t}$-event in the ILD detector, showing the individually reconstructed neutral and charged particles. The colour code presents the particle flow algorithm reconstruction without reference to the Monte Carlo generator information.

V. SOFTWARE AND COMPUTING

It will only be possible to meet the physics goals of the ILC programme if the excellent detector resolution of the two proposed ILC detector concepts described above is complemented with powerful and sophisticated algorithms for event reconstruction and data analysis. For over a decade, the ILC community has developed and improved its software ecosystem *iLCSoft* [19], which is based on the event data model LCIO [20], and the generic detector description toolkit DD4hep [21]. The iLCSoft tools are used by both ILC detector concepts and also by CLIC. From the start, a strong emphasis has been placed on developing flexible and generic tools that can easily be applied to other experiments or new detector concepts. This approach of developing common tools wherever possible has helped considerably in leveraging the limited manpower and putting the focus on algorithm development that is crucial for the physics performance.

A development of particular importance is the refinement of the PFA technique that aims to identify and reconstruct every individual particle created in the event in order to choose the best possible subdetector measurement for every particle. An example of individual particles reconstructed using PFA in a $t\bar{t}$-event is shown in Fig. 6.

Both detector concept groups have invested considerable effort into making their full-simulation models as realistic as possible. Starting from a precise description of the actual detector technology, passive material, gaps and imperfections have been added. Care has been taken to include realistic services such as cables and cooling pipes, in particular in the tracking region where the material budget has a direct impact on the detector performance. These simulation models have been used for large-scale Monte Carlo production and physics analyses for the TDR and more recent detector optimisation campaigns. Based on these studies, a realistic understanding of the expected detector performance and the physics reach of the ILC for both detector concepts has been achieved.

The development of *iLCSoft* has been a truly international activity, in which European groups, in particular DESY and CERN, have played a leading role. They will expand efforts if the ILC is approved. The next stage will focus on adapting the software tools for modern hardware architectures and continue to improve the computing and physics performance of the algorithms.

An initial computing concept for the ILC, including a first estimate of the required resources, has been developed by the LCC Software and Computing Group [22]. This concept follows in general terms that of the LHC experiments and Belle II, with a strong on-site computing center complemented by large Grid-based computing resources distributed around the world. Due to the much lower event rates at the ILC compared to the LHC, the detectors will run in an un-triggered mode in which data from every bunch crossing will be recorded. At the detector site, only limited computing resources are required for online monitoring, QA, and data-buffering for a few days. Prompt reconstruction, event building, and filtering of the interesting collisions will be performed at the main ILC campus. A few percent of the data will be distributed to major participating Grid sites in the world for further skimming and final redistribution for physics analysis. A copy of the raw data from all bunch crossings will be kept to allow for future searches for new exotic signatures. Based on detailed physics and background simulations, the total raw data rate estimate of the ILC is $\sim$1.5 GB/s. The total estimated storage needs will be a few tens of PB/y. The computing power needed for simulation, reconstruction, and analysis will be a few hundred kHepSpec06. Given that these numbers are already smaller than what is now needed by the LHC experiments, and given an expected annual increase of 15% and 20%, respectively, for storage and CPU at flat budget, the overall computing costs for the ILC will be more than an order of magnitude smaller than those for the LHC.

VI. DISCUSSION AND SUMMARY

The ILC has a mature technical design that is ready for construction. The ILC will start as a Higgs boson factory (ILC250). Here the clean operating environment, low backgrounds, and adjustable beam energies and polarisations will allow model-independent measurements of the Higgs boson's mass and CP properties and of its absolute couplings to SM fermions and gauge bosons, most of them to better than 1% precision. These measurements will discriminate between the SM and many different BSM models. The ILC will be sensitive to invisible and other exotic Higgs decays, accessing additional new physics models including models of Dark Matter. The ILC polarised beams offer additional precision tests of the SM, in particular for the electroweak couplings of right-handed fermions, which are largely unconstrained today.

The ILC can be extended to higher energies in possible future upgrades, up to 500 GeV and 1 TeV. In these later stages, the ILC will give access to the properties of the top quark, including the top-quark Yukawa coupling, and to the Higgs self-coupling. Above the top-quark production threshold, the ILC will be a precision top-quark factory. Throughout its energy evolution, the ILC will be able to produce pairs of new BSM particles of mass up to half its centre-of-mass energy and to provide sensitivity to new force particles Z' well beyond the direct search reach of the LHC.

Since no new particles beyond the SM have been discovered at the LHC, the search for new physics through high-precision studies at the electroweak scale, particularly the Higgs boson and the top quark, has become urgent and compelling. These studies strike at the heart of the mysteries of the SM in a way that is orthogonal to direct searches for new particles. As discussed in Section II, the ILC capabilities for precision tests will be qualitatively superior to those of the high-luminosity LHC. This makes the ILC a powerful complement to future LHC particle searches, with the ability to discover the new interactions that underlie the SM.

The goal of a precise understanding of the Higgs boson is attractive in its own right, readily communicated to our scientific colleagues in other disciplines, as well as the general public. Together with this goal, the ILC provides a fully formed project proposal with a cost estimate similar to that of the LHC, a moderate time scale, and well tested technologies for its detector and accelerator designs.

Future circular e^+e^- colliders have been proposed as an alternative method for precision Higgs boson studies. These have the potential to deliver higher luminosity at energies up to about 300 GeV. However, the ILC, operated as a Higgs factory, can take advantage of beam polarisation to achieve similar physics performance [3]. More importantly, the straightforward energy upgrade path of the ILC makes the Higgs factory stage only the first phase of its potential for exploration.

As emphasised in the previous sections, the ILC proposal is supported by extensive R&D and prototyping, both for the accelerator and for the detectors. For the accelerator, the successful construction and operation of the European XFEL at DESY gives us confidence both in the high reliability of the basic technology and in the reliability of its performance and cost in industrial realization. For the detector, an extensive course of prototyping underlies our estimates of full-detector performance and cost. Some specific optimizations and technological choices remain. But the ILC is now ready to move forward to construction.

The ILC TDR cost has been rescaled for ILC250 [2] and has recently been futher re-evaluated incorporating items specific to Japanese construction and accounting. The current quoted cost estimate of the ILC250 is shown in Appendix A. This cost has been scrutinised in a number of studies, most recently by a working group of the Japanese MEXT ministry, as described below. Here too, the ILC is ready to move forward.

A strong community of universities and laboratories world-wide is ready to realise the ILC, to develop its detectors, and to exploit its physics opportunities. The ILC Technical Design Report was signed by 2400 scientists from 48 countries and 392 institutes and university groups, as described in Appendix B. This community continues to prepare for the scientific program and will expand its efforts once the ILC is launched as a project.

The ILC R&D program and the construction of the FELs based on SCRF in Europe, the US, and Asia, has opened strong links between the ILC community and industry. Very productive networking and communication has been established between industry representatives and scientists. Since 2016, all linear collider conferences have included one-day mini-workshops to show and promote industrial opportunities. These industrial mini-workshops have been well attended with growing interest and participation from individual companies and from the industrial associations of several key countries.

On the political side, broad interest for the ILC in Japan has been steadily growing. The plan for hosting the ILC in Japan is being promoted by political entities, at the Japanese Diet and at the provincial levels, by a large industrial consortium (AAA), and by representatives of the particle physics community (JAHEP). Since 2013, the ILC project has been examined extensively by the MEXT ministry within a cautious official procedure, in which minimising risks is of prime importance. MEXT's ILC Advisory Panel released its report [23] on July 4, 2018. This report summarises the studies of the several working groups (WG) that reviewed a broad range of aspects of the ILC. The most recent studies include a specific review of the scientific merit and the technical design for the ILC250. The Physics WG scrutinised the scientific merit of the ILC250, leading to their strong and positive statement on the importance of the ILC250 to measure precisely the couplings of the Higgs boson [23]. The TDR WG reviewed issues addressed in the Technical Design Report and the ILC250 design, including the cost estimate and technical feasibility. Other working groups of the MEXT review commented on manpower needs, organisational aspects, and the experience of previous large projects. The report of the ILC Advisory Panel was followed by the beginning of deliberations in a committee and technical working group established by the Science Council of Japan (SCJ). Another independent committee (ILC Liaison Council), led by leaders of the Liberal Democratic Party, the majority party in the Diet, has now convened to encourage the national government to proceed with the ILC.

It is an important aspect of the discussions of ILC in Japan that the ILC is seen as a global project that will foster exchange between Japan and other nations. Thus, the scientific interest and political engagement of partner countries is a major concern for the Japanese authorities. For example, Japan has now begun efforts to secure US partnership in the ILC. The US Department of Energy Under Secretary for Science recently visited Japan; he attended meetings with political leaders promoting the ILC, and with the leadership of KEK, and stated the US would look forward to a dialog on an ILC project.

Europe's technological expertise and its scientific strength make it a valued potential partner. Japan is approaching Europe both through bilateral discussions with individual countries, in which ILC may appear in a broader landscape embracing other advanced technology topics, and through direct engagement with CERN. It is our hope that CERN will play a leading role in the European participation in the ILC, along the lines described in the conclusions of the 2013 Update of the European Strategy, and also in a similar fashion to that developed for the European participation in the US neutrino program.

ILC is an energy-frontier project that can be started today. It will provide a new opportunity for European physicists in the time frame of the HL-LHC and beyond, as Europe plans and marshals its resources for the next major CERN project. In this way, the ILC will play a crucial role in encouraging a new generation of researchers to enter particle physics and maintain the continuous tradition and the scientific strength of our enterprise.

In summary, a large world-wide community of particle physicists is eager to join the effort to build the ILC and its detectors, and to pursue its unique physics program. The machine technology is mature and construction-ready. The envisaged timeline of the project includes 4 years of preparation phase and 9 years of construction. The ILC will deliver unique contributions in our effort to probe beyond the Standard Model to an ultimate understanding of the fundamental laws of nature. The scientific case for the ILC has become irresistible.

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